NUMERICAL ANALYSIS OF THE PERFORMANCE OF ROCK WEIRS: EFFECTS OF STRUCTURE CONFIGURATION ON LOCAL HYDRAULICS

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ABSTRACT

River spanning rock structures are being constructed for water delivery as well as to enable fish passage at barriers and provide or improve the aquatic habitat for endangered fish species. Current design methods are based upon anecdotal information applicable to a narrow range of channel conditions. The complex flow patterns and performance of rock weirs is not well understood. Without accurate understanding of their hydraulics, designers cannot address the failure mechanisms of these structures. Flow characteristics such as jets, near bed velocities, recirculation, eddies, and plunging flow govern scour pool development. These detailed flow patterns can be replicated using a 3D numerical model. Numerical studies inexpensively simulate a large number of cases resulting in an increased range of applicability in order to develop design tools and predictive capability for analysis and design.

The numerical model U^{2}RANS is used to investigate how variations in structure geometry affect local hydraulics, scour hole development, and overall structure performance. An automatic mesh generator was developed to expedite the process of generating 30 structure geometries in a simulated straight trapezoidal channel. Variations in structure geometry include: arm angle, arm slope, drop height, and throat width. Various combinations of each of these parameters are modeled at 3 flow rates: 1/3 bankfull discharge, 2/3 bankfull discharge and bankfull discharge. The numerical modeling focuses on how variations in structure geometry affect local flow patterns and scour development. Numerical modeling results duplicated both field observations and lab results by quantifying high shear zones near field and lab scour areas and low shear zones near field and lab depositional areas.

The analysis and results of the numerical modeling, laboratory modeling, and field data provide a process-based method for understanding how structure geometry affects flow characteristics, scour development, fish passage, water delivery, and overall structure stability. Results of the numerical modeling allow designers to utilize results of the analysis to determine the appropriate geometry for generating desirable flow parameters. The end product of this research will develop tools and guidelines for more robust structure design or retrofits based upon predictable engineering and hydraulic performance criteria.

1 INTRODUCTION

River spanning rock structures provide sufficient head for irrigation diversion, permit fish passage over barriers, protect banks, stabilize degrading channels, activate side channels, reconnect floodplains, and create in-channel habitat. Vertical drop height, lateral constriction, size of rock material, and construction methods are common design considerations for these structures. The use of in-stream structures for habitat and stream restoration dates back to the early 1900s; however, the design, effectiveness, and performance of these types of structures have not been well documented. A review of international literature on grade control structure design by Nagato (1998) found that no official standard guidelines for designing low-head drop structures exist. The review found that design guidelines were relatively tentative or provisional and site specific in nature. While recently there have been a large number of laboratory experiments and empirical relationships developed from field data, efforts to link these relationships with field engineering practices are lacking.

Monitoring of in-stream restoration projects has focused primarily on whether structures produce the desired physical response rather than understanding the physical processes that cause the physical response and how that response might change with differing structure configurations. While general monitoring of in-stream restoration projects provides some information pertaining to success and failure rates, it usually does not provide enough detailed quantitative information to determine the physical processes associated with the success or failure of a given structure geometry. As a result, current design methods are based upon anecdotal information applicable to narrow ranges of channel conditions. Complex flow patterns and performance of rock weirs are not understood, and methods and standards based upon predictable engineering and hydraulic performance criteria currently do not exist. Without accurate hydraulics, designers cannot address the failure mechanisms of structures.

In 2005, the Bureau of Reclamation (Reclamation) initiated a program to evaluate the performance of these structures and develop design guidelines using a multi-faceted approach that consists of field reconnaissance, physical modeling, and numerical modeling. Integration of field, lab, and numerical data sets provides a scientific basis for predicting structure performance under various river conditions and for developing the most-effective design criteria. This paper focuses on the numerical modeling of rock weirs and the effects that variations in the structure geometry have on local hydraulics. A design matrix consisting of approximately 30 different structure configurations along with a field validation case are presented. The following section takes a closer look as to why lower order (1D and 2D) models are not suitable for simulating the complex flow patterns associated with rock weirs.

2 PRELIMINARY COMPARISON OF NUMERICAL MODELING OF ROCK WEIR FLOW PATTERNS

Numerical modeling provides an opportunity to test design parameters over large ranges. A numerical model must capture significant flow patterns and replicate the important dominant physical processes. One-dimensional (1D) numerical simulations model downstream changes in hydraulics while neglecting vertical and lateral variation. Two-dimensional (2D) models incorporate lateral differences in velocity and water surface elevation, but neglect flow patterns that are not parallel to the stream bed. Three-dimensional (3D) modeling simulates the motion of water in all directions and most accurately captures flow patterns. Estimating structure performance with lower dimensional methods requires understanding the impact of representing a feature with methods farther divorced from real world processes. The limited understanding of the complex flow patterns around rock weirs require 3D simulations.

Flow characteristics such as jets, near bed velocities, recirculation, and plunging flow govern scour pool development. 3D numerical models capture these patterns without requiring prior and possibly incorrect assumptions typically required when using lower order models. Figure 1 shows a U-Weir in the field and the corresponding water surface and velocity output from the 3D numerical model U^{2}RANS (Lai et al, 2003). In the photograph, entrained air reveals areas of high velocity and turbulence. The 3D model captured flow features including the draw down curve, hydraulic jump, and variations in velocity. Dry areas in the photograph, such as the protruding rocks in the upper left corner match the 3D model water surface. Figure 1 demonstrates the capability of three-dimensional numerical modeling to match field conditions.

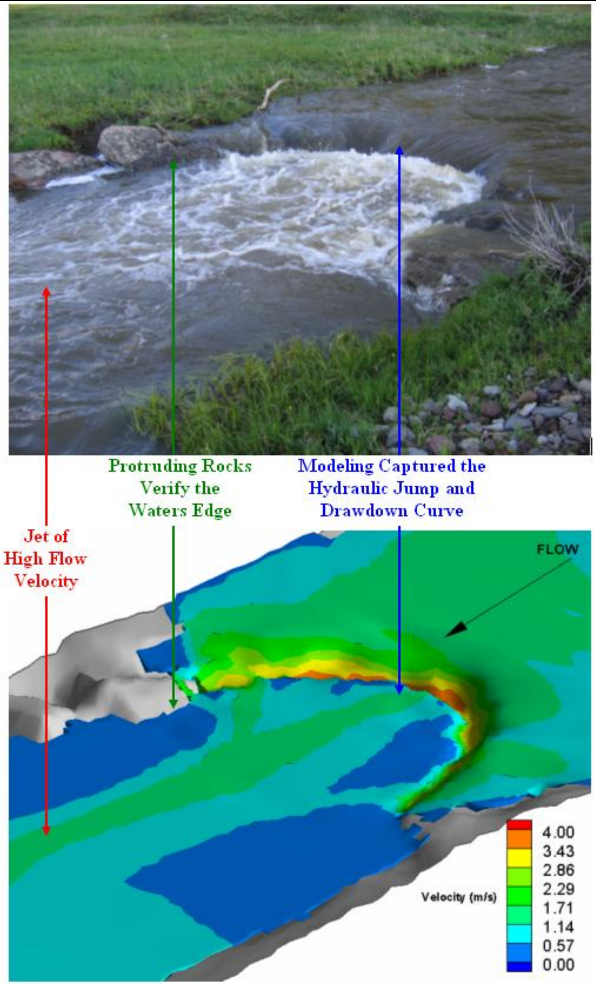

Figure 1. Field Photo and Corresponding Numerical Modeling Results

Figure 2 shows a plan view with water surface elevation contours. The areas upstream and downstream of the structure show little lateral variation. The water surface drops rapidly over the structure and follows the weir crest topology. 1D modeling assumes gradually varied flow and constant water surface elevation across a transect. Methods to meet 1D water surface requirements include constructing cross sections tracing water surface elevation contours or coding multiple cross section perpendicular to the thalweg.

Figure 3 shows surface velocity vectors. In the channel upstream and downstream of the structure water generally flows parallel to the banks. Over the weir, the flow paths rapidly converge and then slowly expand. A jet through the center of the channel creates abrupt lateral changes in velocity. 1D modeling requires cross section lines perpendicular to the velocity vectors and therefore must accommodate lateral variability through bending the cross section.

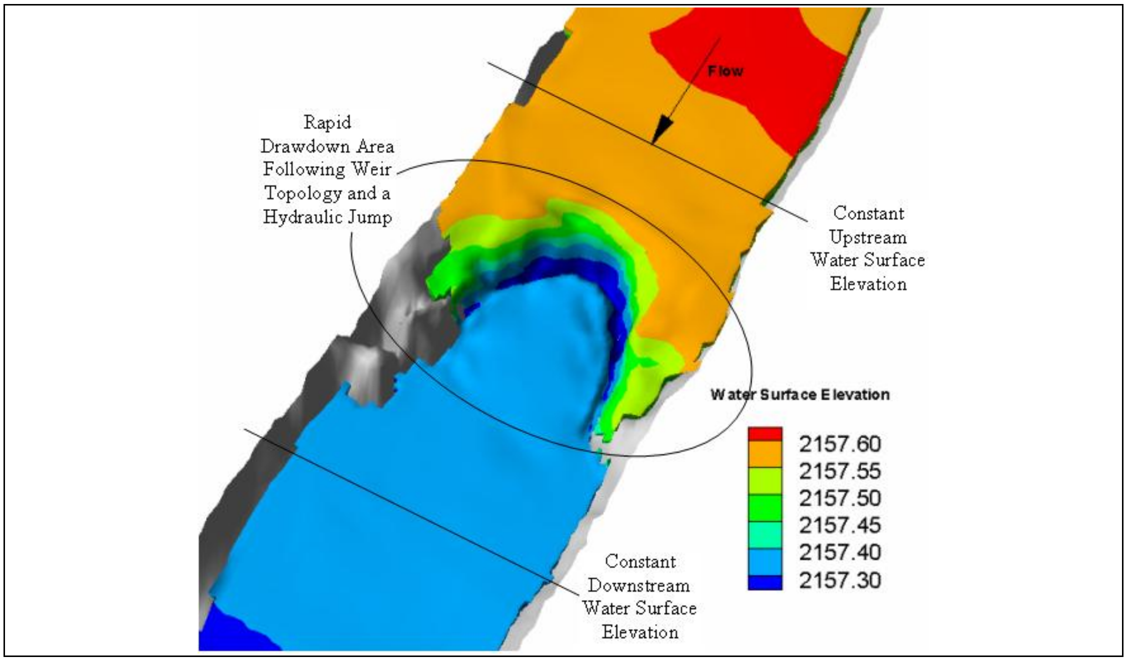

Figure 2. Modeled Water Surface Elevation (Z-Axis Scaled Factor of 5)

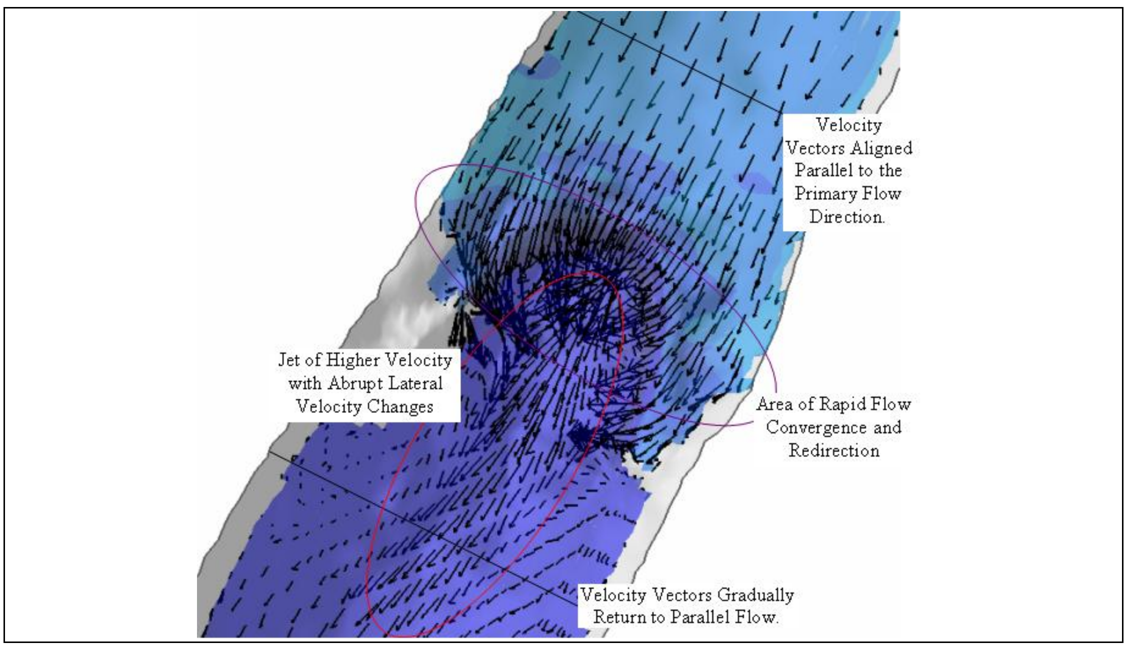

Figure 3. Plan View Velocity Vectors and Wetted Area

Figure 4 shows a vertical profile view for velocities along a longitudinal section of the thalweg. Water flows parallel to the bed upstream and downstream of the structure. The stream lines rapidly converge and diverge vertically through the structure. The velocity profile contains a jet midway through the water column rather than the logarithmic profile of a typical river section. Vertical velocity components in the scour pool show plunging flow. 2D modeling requires velocity vectors perpendicular to a vertical plane while 1D modeling requires perpendicular velocity vectors in both vertical and lateral planes. As a result, these lower order models are not able to properly represent the flow patterns associated with these types of structures.

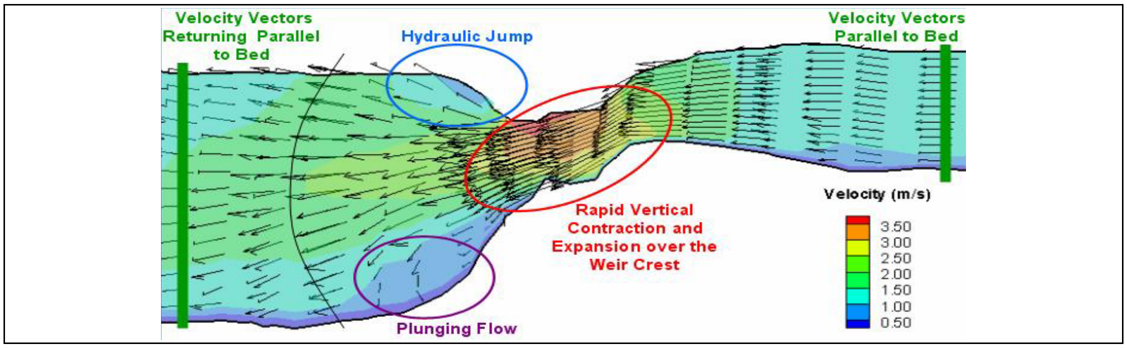

Figure 4. Thalweg Profile View and Velocity Magnitude

Figure 5 illustrates attempts to reconcile the cross sectional 1D requirement with observed field conditions. A cross section model can meet either water surface requirements or velocity requirements, but not both. Figure 5 demonstrates why 1D models require adjustments for multi-dimensional effects. HEC-RAS contains placeholders, but the magnitude of the adjustment is unknown for rock weirs. The adjustment will depend on the throat width, profile and plan arm angle, drop height, and more. After understanding the 3D processes, developing 1D and 2D adjustment parameters may be possible.

In addition to the field data comparison, with the recent completion of the rock weir laboratory testing, measured water surface elevations, velocities, and bed topography are currently being analyzed and compared to results from the 3D numerical model in order to develop rating curves and scour prediction equations for various rock weir configurations.

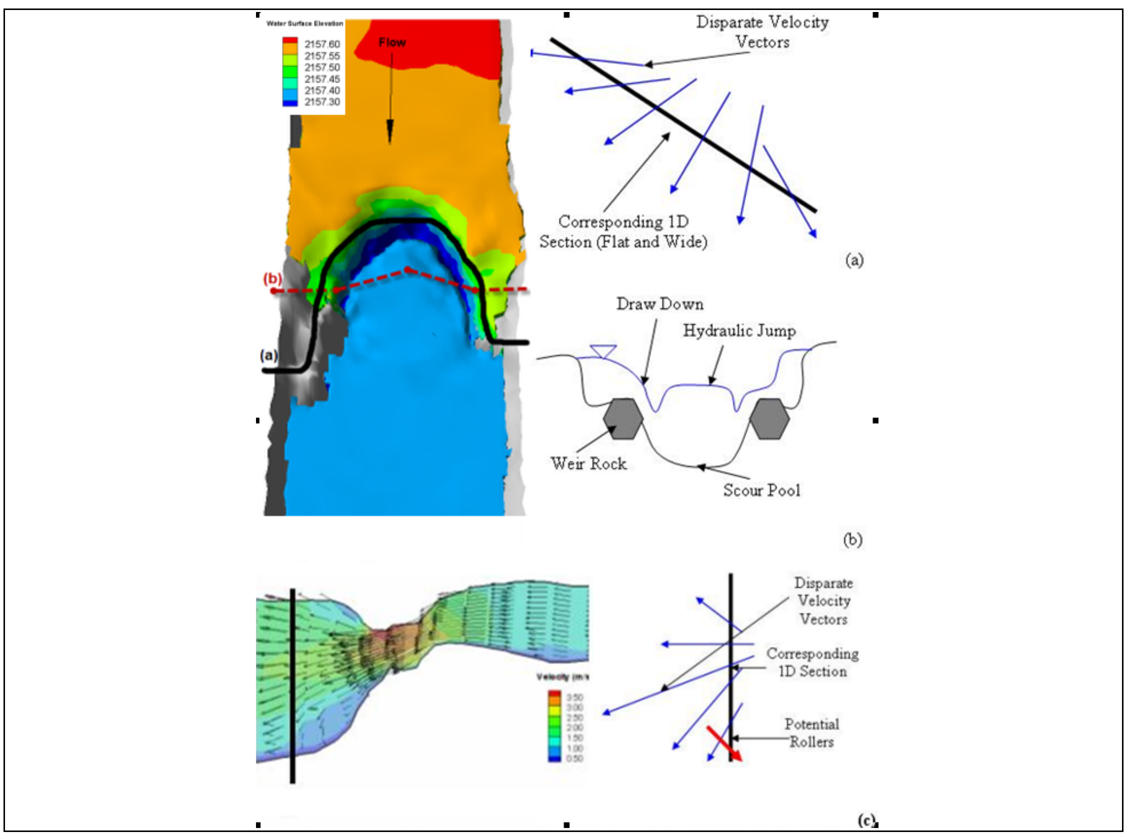

Figure 5. Meeting 1D Water Surface Criteria Fails to Meet Velocity Criteria (a) and vice versa (b). No Method captures jumps or plunging flow (c).

3 3D MODEL SETUP AND DESIGN

The numerical model U^2RANS (Lai et al, 2003) is used to investigate how variations in structure geometry affect local hydraulics, scour hole development, and overall structure performance. An automatic mesh generator was developed to expedite the process of generating 30 different structure geometries in a simulated straight trapezoidal channel. Variations in structure geometry include: arm angle, arm slope, drop height, and throat width. The following sections describe how the design matrix was generated.

3.1 Included Variables

The following variables were included in compiling the final design matrix:

- Bed Material
- Channel Slope
- Throat Width
- Drop Height (fish passage criteria per WDFW 2003)
- Arm Length (Planform Angle and Profile Angle)

3.2 Excluded Variables

The following variables were considered but not included in the final design matrix:

- Bank Height: Water depths will not exceed weir depth. All model runs are at bank full or less, no superbank discharge.
- Bank Angle (Side Slope): 0.75:1 (H:V) Assuming wide-rectangular is adequate.
- Top Width: set by hydraulic geometry equations.
- Bankfull Design Discharge: set by hydraulic geometry equations.
- Asymmetric Geometries: This is a limitation of the study scope.
- Radius of Curvature: This is a limitation of the study scope.

3.3 Matrix Configuration

3.3.1 Bed material

Grain sizes were selected to match field conditions in which river spanning rock structures are most commonly used (ie. gravel bed rivers). The distributions for the D84 and D16 were set to plus and minus one phi class. Three D50 grain diameters were selected using the geometric mean of the AGU classification system, a log base 2 scale:

- Coarse Gravel: D50 = 22.63 mm, D84 = 45.25 mm, D16 = 11.31 mm
- Small Cobble: D50 = 90.51 mm, D84 = 181.0 mm, D16 = 45.25 mm
- Large Cobble: D50 = 181 mm, D84 = 256 mm, D16 = 90.51 mm

3.3.2 Bankfull Channel Geomerty

Previous research has shown that it is possible to define a ‘‘bankfull channel geometry’’ [Leopold and Maddock, 1953; Leopold et al., 1964] in terms of a bankfull width B_{bf}, bankfull depth H_{bf} and down-channel bed slope S. More recently, Parker et al. (2007) used a baseline data set consisting of four differing stream reaches from Canada, USA, and Britain to determine bankfull hydraulic relations for alluvial, single-thread gravel bed streams with definable channels and floodplains. Their results (eqns, 1-3 below) show a considerable degree of universality and the exponents of Q_{bf} in these equations are similar to those found by other authors (e.g., Millar, 2005).

$$S \cong 0.101 \cdot \left(\frac{Q_{bf}}{\sqrt{gD_{s50}}D_{s50}^2} \right)^{-0.344} \qquad \text{Equation 1}$$

$$W_{bf} \cong \frac{4.63}{g^{1/5}} Q_{bf}^{0.4} \left(\frac{Q_{bf}}{\sqrt{gD_{s50}}D_{s50}^2} \right)^{0.0667} \qquad \text{Equation 2}$$

$$H_{bf} \cong \frac{0.382}{g^{1/5}} Q^{2/5} \qquad \text{Equation 3}$$

Where,

S = bed slope;

Q_{bf} = bankfull discharge (m^3/s);

D_{s50} = median particle diameter, (m);

W_{bf} = bankfull width (m);

H_{bf} = bankfull depth (m).

Because of the degree of universality and ease of use of the hydraulic geometry equations presented by Parker et al., they were selected for determining the bankfull hydraulic geometry used in this study. Given the bed material grain sizes listed above and a range of representative channel slopes (0.001, 0.004, and 0.01), Equations 1, 2, and 3 were used to compute central width, depth, and discharge tendency in the design matrix. In order to analyze each structure configuration and its effects on the local flow patterns, the discharge for each structure configuration was varied to include 1/3, 2/3, and bankfull discharges.

3.3.3 Throat width

Initial structure throat width was set to 1/3 the bankfull width as specified in Rosgen (2001) and following observed field applications. To study how flow patterns are affected by changes in structure throat width, the throat width was varied from 1/4, 1/3, and 1/2 the calculated bankfull width for each of the three grain sizes and corresponding channel geometry.

3.3.4 Drop height

Drop height was set to 0.8ft as prescribed by the WDFW (2003) for the maximum drop height allowed for fish passage. In order to study how the drop height over the structure effects flow patterns, this parameter was varied by 0.5 and 1.5 times the value prescribed by WDFW (2003). This results in a range of drops heights of 0.4, 0.8, and 1.2ft.

3.3.5 Arm length

Initial structure arm lengths were designed to approach as close as possible the midpoint of the design ranges specified in Rosgen (2001). Rosgen's recommended plan angles were between 20 to 30 degrees and profile angles range from 2 to 7 percent. Target angles were 25 degrees for plan angles and 4.5 percent for profile angles. The solver function in Microsoft Excel® was then used to calculate the weir arm length that minimized the relative distances on the planform and profile angles of the weir arms. This minimized solution was then used to calculate the arm length ranges that would be used in the numerical modeling in two ways;

multiplying the minimized values by ½ and 2. This provided a wide range of planform (10.31 to 48.35 degrees) and profile angles (1.47 to 10.11 percent) to be tested (Figure 6).

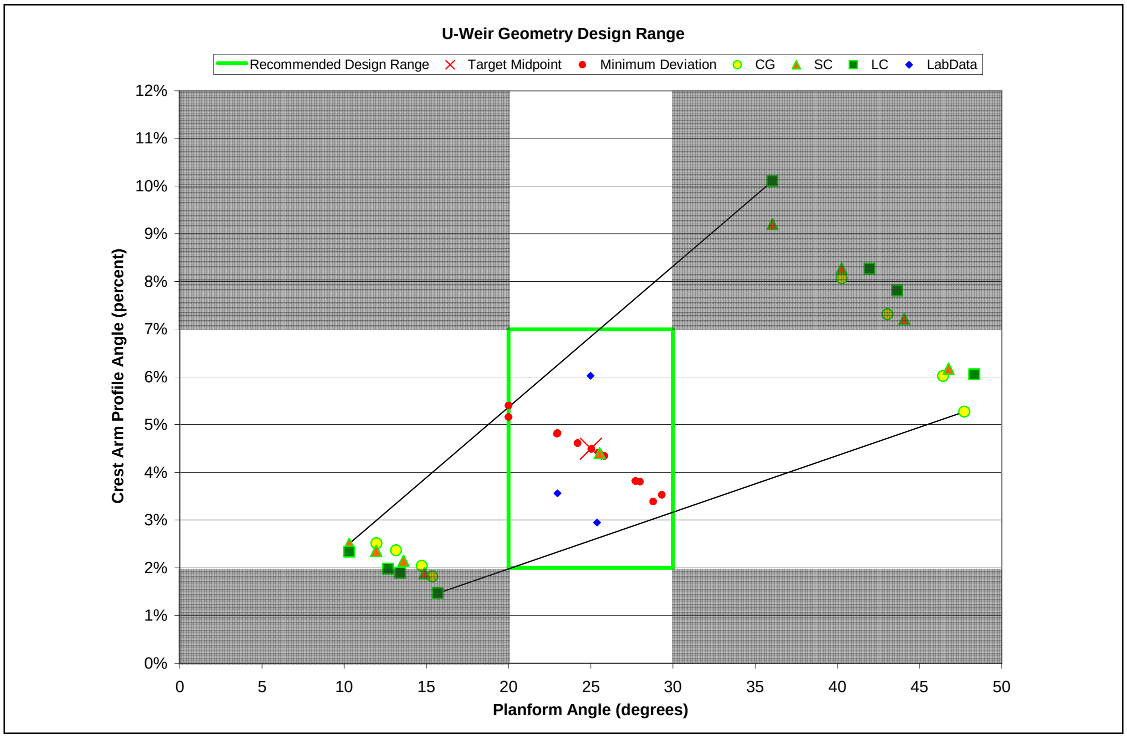

Figure 6. Plot of variation in structure parameters used in design matrix.

3.4 Mesh Generator

The automesh generator simplifies the process of 3D numerical modeling by allowing the generation of multiple structure geometries in a quick and cost effective manner. Five lateral definition lines describe a structure in the 3D mesh generator: upstream bed, upstream header, downstream header, downstream footer, and downstream bed. Overbank, top of bank, and toe lines describe the channel. Each line consists of eight definition points. Combinations of river left or river right, toe, top of bank or overbank, upstream or downstream, bed, header or footer, and pool uniquely identify each definition point. Dashed lines show the intersection of the structure with the channel bank. Each point can be uniquely identified through selecting one from each column in Table 1. Figure 7 shows the conceptualized structure with definition lines and definition points.

Table 1. Structure Definition Point Identification

Flow-Wise	Bank-Wise	Structure-Wise	Laterally
Upstream	Left	Bed	Throat
Downstream	Right	Header	Toe
		Footer	Top bank
		Pool	Overbank

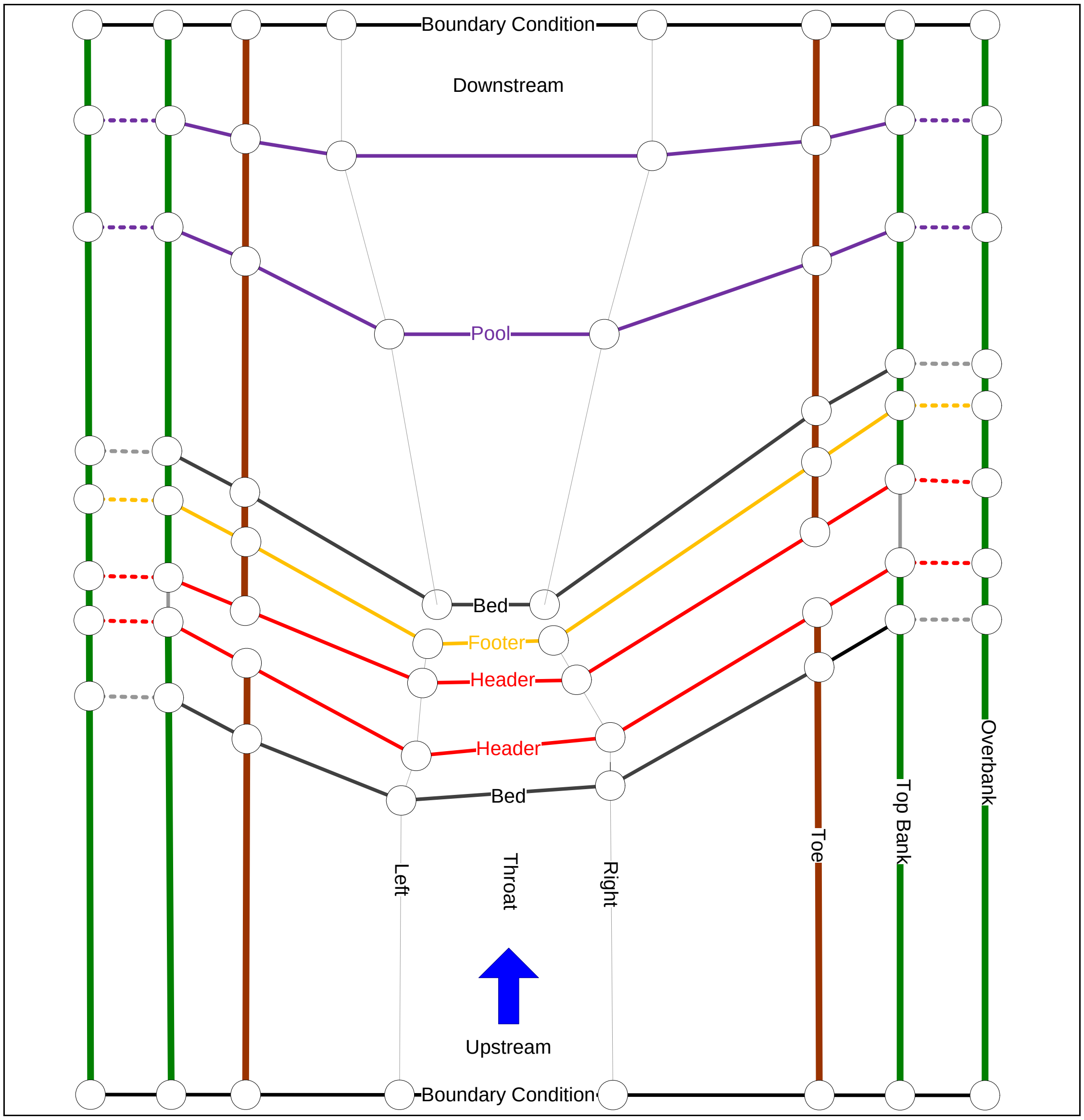

Figure 7. Profile of 3D Structure Line and Point Definition

The definition lines can be identified by the endpoints. For example, the line from the downstream right footer toe to the downstream right footer top of bank identifies where the downstream face of the structure intersects the bank on river right (looking downstream). Definition lines create structure faces that can be identified as left arm, throat, and right arm.

4 PRELIMINARY ANALYSIS OF STRUCTURE CONFIGURATION AND RESULTING HYDRAULICS

Analysis of the effects that variations in rock weir arm length (arm angle and slope), throat width, and drop height have on local hydraulics is currently underway. The following are being analyzed to determine how variations in structure geometry affect local hydraulics: velocity field, bed shear stress, conveyance or flow constriction, energy dissipation, eddies and flow re-direction, and near bank velocities and shear stresses. Figure 8 and Figure 9 show how the velocity field and bed shear stresses are altered for various structure configurations.

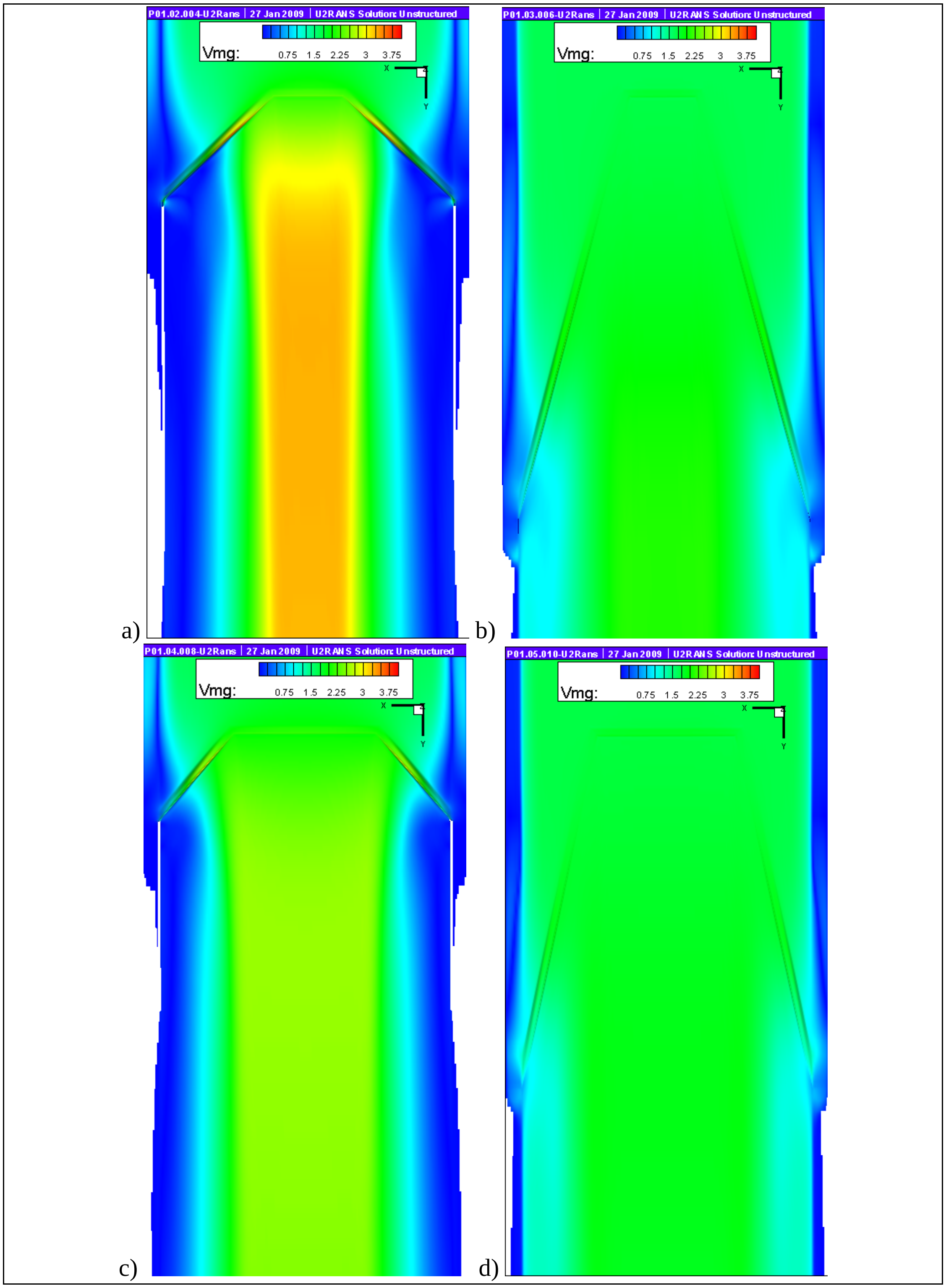

Figure 8. Change in surface velocity for various structure configurations: a) .25Width-.5Arm Length, b) .25Width-2Arm Length, c) .5Width-.5Arm Length, d) .5Width-2Arm Length.

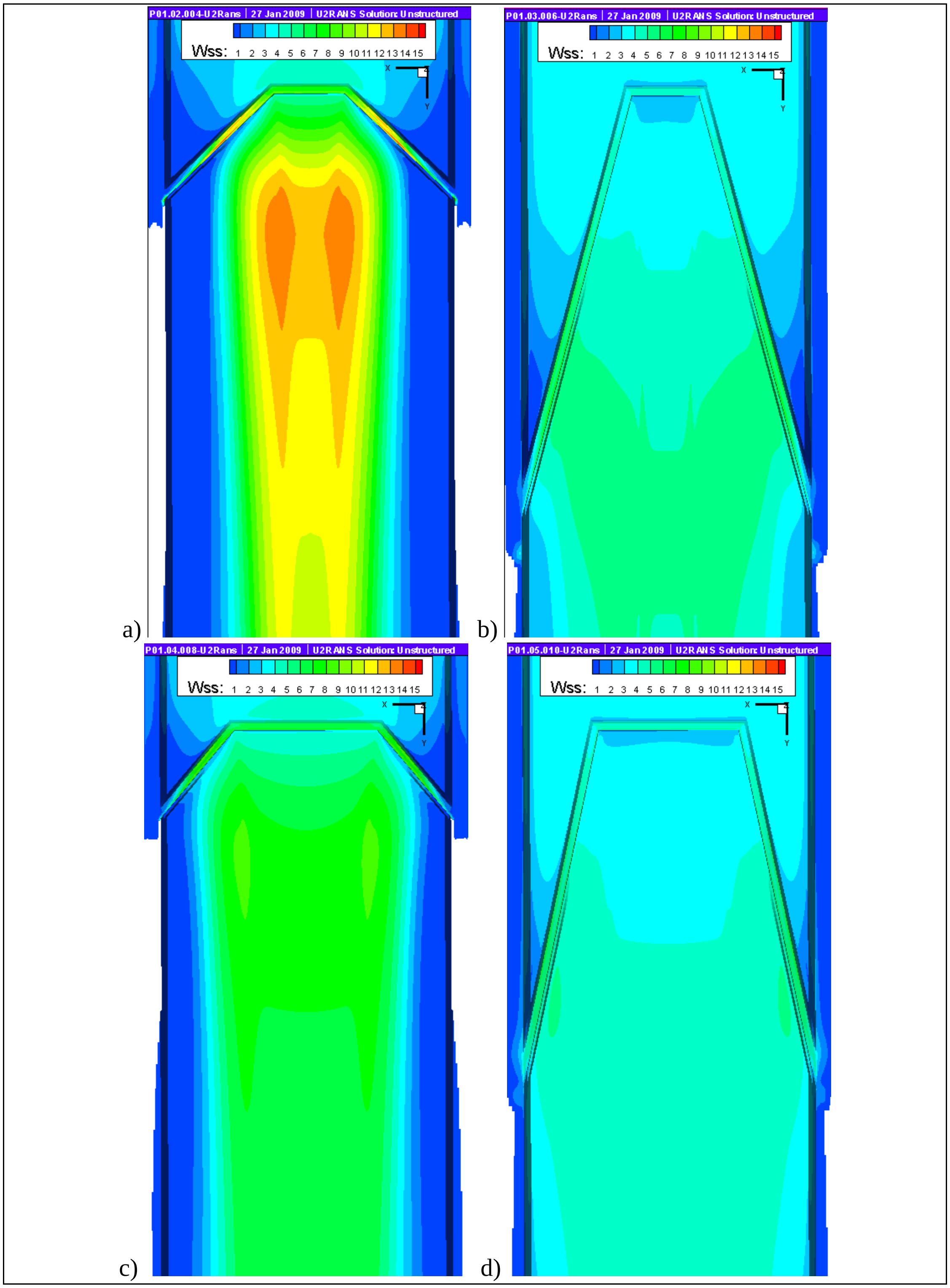

Figure 9. Change in bed shear stress for various structure configurations: a) .25Width-.5Arm Length, b) .25Width-2Arm Length, c) .5Width-.5Arm Length, d) .5Width-2Arm Length.

5 CONCLUSIONS

The numerical modeling focuses on how variations in structure geometry influence local flow patterns and scour development. Current numerical modeling results have duplicated both field observations and laboratory results by quantifying high shear zones near field and lab scour areas and low shear zones near field and lab depositional areas. Results of the numerical modeling allow designers to determine the appropriate geometry for generating desirable flow parameters. The results may also be coupled with the results of the physical model to develop a method to predict critical variables, such as bed shear stress and scour depths, using a 1D model.

The analysis and results of the numerical modeling, laboratory modeling, and field data provide a process-based method for understanding how structure geometry affects flow characteristics, scour development, fish passage, water delivery, and overall structure stability. The end product will develop tools and guidelines for more robust structure design or retrofits based upon predictable engineering and hydraulic performance criteria.

6 REFERENCES

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